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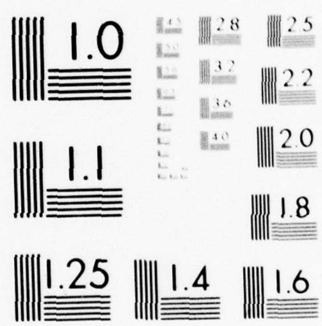

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LEVEL II 12

LOW NOISE EBS JAMMER

FIRST TRIANNUAL REPORT

28 July 1978 through 30 November 1978

Contract No. DAAB 07-78-C-2958
File No. WJ-78-4172TR1

Prepared by:
D.B. Clark
J.B. Rettig

Watkins-Johnson Company
3333 Hillview Avenue
Palo Alto, California 94304

for

U.S. Army Electronics Technology & Devices Laboratory
Electronics Research and Development Command
Fort Monmouth, New Jersey 07703

FOREWORD

Identification of Engineering Personnel

Douglas B. Clark, Project Engineer
Salvatore Spinella, Program Manager
John B. Rettig, Member of Technical Staff

Descriptive Background of Key Personnel

Biographical sketches for each of the key personnel are included in the Appendix.

Publication, Lectures, Reports and Conferences

1.	Publications	None
2.	Lectures	None
3.	Reports	Monthly Status Reports July 1978 through November 1978
4.	Conferences	Progress on subject contract. Watkins-Johnson Company personnel and Mr. Robert M. True of ERADCOM, Fort Monmouth, N.J. Held at Watkins-Johnson Company on 11-13 December 1978.

Program for the Next Internal

The Program Plan shown in Figure 2-2 and described in Section 6.0 represents our best estimate of work to be carried out during the next reporting period.

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Electron Gun
Diode

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The objective of this program is to reduce the output power level of spurious noise signals, intermodulation (IM) products and harmonic distortion generated by deflection modulated electron beam semiconductor (EBS) amplifiers. Work accomplished during the reporting period included identification and theoretical investigation of causes of nonlinearity and measurements of linearity, noise and distortion of existing EBS amplifiers.

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1.0 INTRODUCTION

1.1 Objective

The program objective is to reduce the output power level of spurious noise signals, intermodulation (IM) products and harmonic distortion generated by deflection modulated electron beam semiconductor (EBS) amplifiers.

1.2 Technical Approach

Figure 1-1 illustrates the configuration of a deflected beam EBS amplifier. This type of amplifier has been developed by Watkins-Johnson over a period of several years. Measurements of existing EBS amplifiers will be made to determine the typical values of IM products, spurious noise and harmonic distortion. The existing electron beam profile will be characterized using a slit beam analyzer. The EBS performance will be correlated to the measured beam profile using a mathematical analysis implemented by a computer program. A second computer program will perform an analysis of the expected beam profile generated by the existing gun geometry and these results will be correlated with the measured beam profile. Modifications will then be performed on the electron gun to improve the linearity, IM products and harmonic distortion, and the re-designed gun will be fabricated and tested on the beam analyzer. Two devices using the re-designed gun will be fabricated, tested and delivered as part of this contract.

2.0 PROGRAM SUMMARY

2.1 Summary of Work

Work performed during this reporting period included measurement of IM products, noise power and harmonic distortion of existing EBS amplifiers. In addition, an existing EBS gun was mounted to a slit beam analyzer and the beam profile was inspected. Calibration of the slit beam analyzer to improve the accuracy of this analysis was also begun. Initial steps were taken toward creating a computer program which will analyze the electron gun geometry to yield a corresponding electron beam density profile. Design of parts for an improved metal-ceramic gun support structure was completed.

2.2 Program Schedule

Figure 2-1 shows the Program Schedule. Schedule slippages will be discussed in the applicable sections.

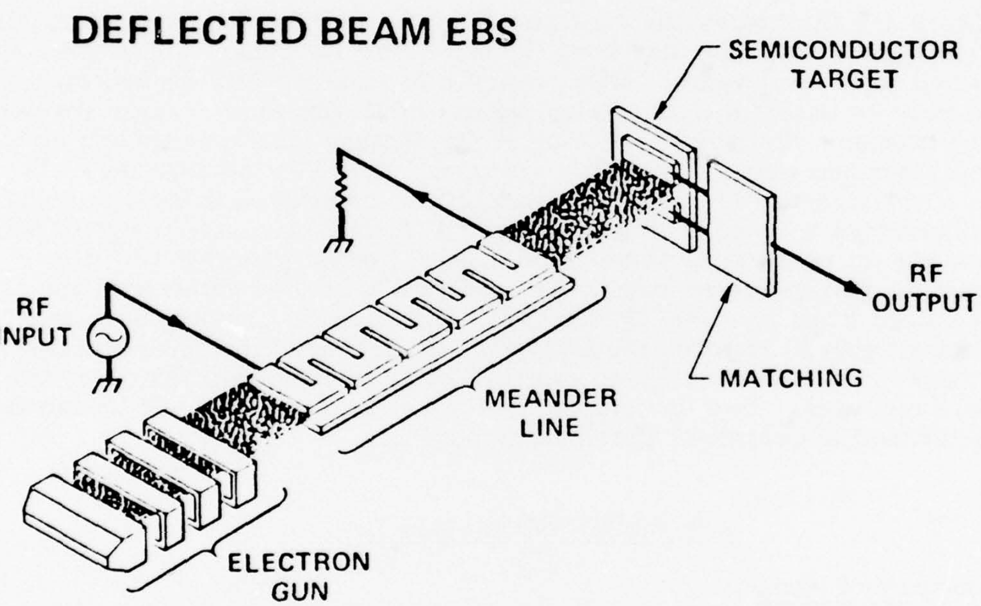

Figure 1-1. Deflected Beam EBS Configuration

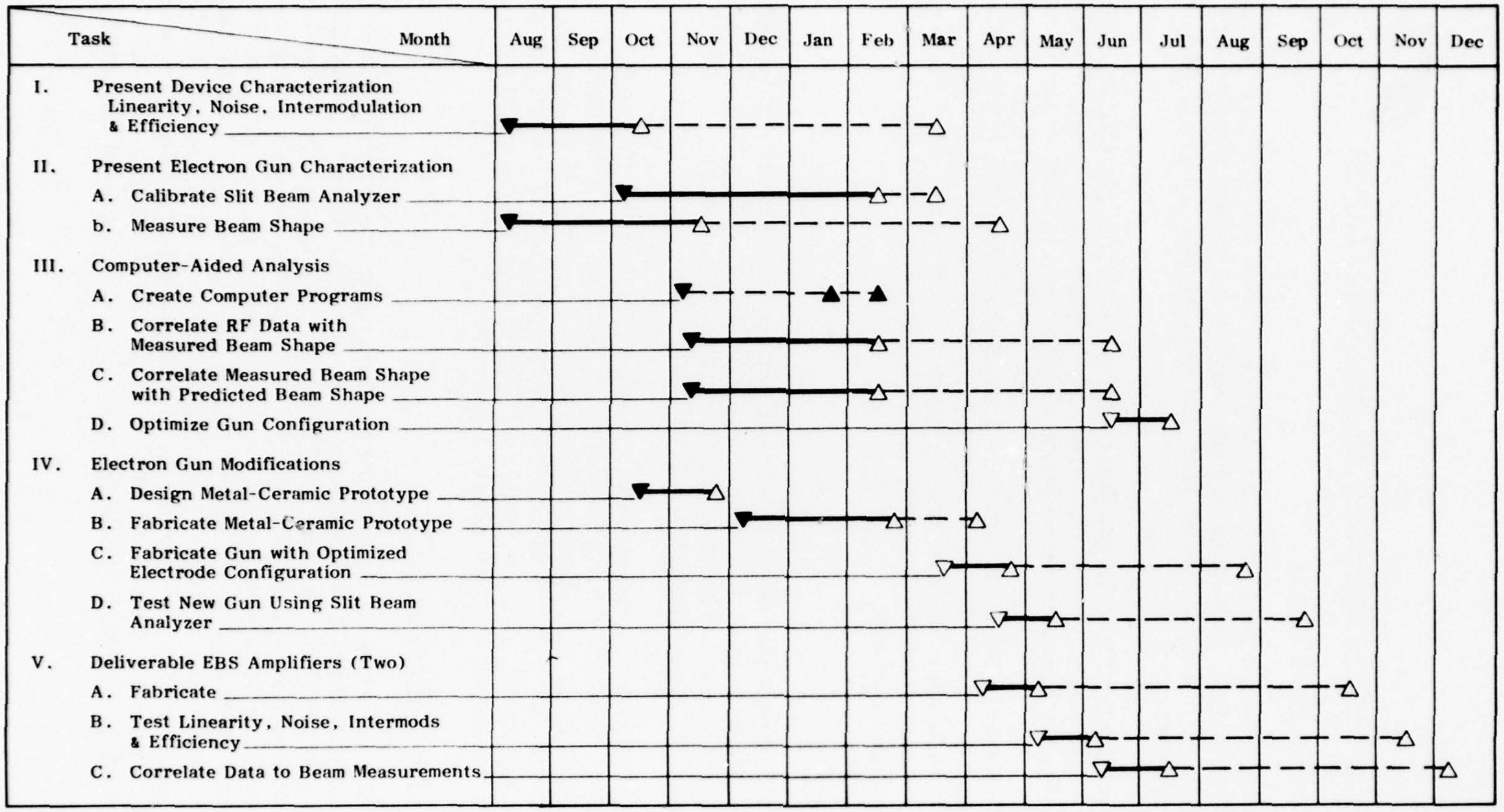

Figure 2-1. Program Milestone Schedule

3.0 CHARACTERIZATION OF EXISTING DEVICES

3.1 Linearity and IM Products

Measurements were performed on deflected beam amplifiers to obtain data on linearity. This data will be used as a reference point for comparison with data obtained from future amplifiers having modified gun structures.

The device electrode voltages were adjusted for nearly optimum linearity and were left unchanged during the measurements. Figure 3-1 shows that the device linearity was within ±1 dB over a 40 dB dynamic range.

Figure 3-2 shows IM data previously measured on a deflected beam EBS amplifier. This data was taken on a tube which had a different cathode and beam size than the latest gun used in the most recent devices, hence further data will have to be taken. This task is shown on the milestone chart.

3.2 Noise Power

Figure 3-3 shows the noise power output as a function of input power and demonstrates that the noise power output tracks quite closely with input signal levels. There is little or no variation in noise power output across the operating band of the EBS.

Figure 3-4 shows the noise output power variation as the beam current is varied so that the saturated output power covers a range of +40 dBm to +50 dBm (10 to 100 watts). To obtain this curve, the beam current was adjusted for a given saturated output power and the input power was then removed. The noise output power per 100 kHz bandwidth was then measured at each point and plotted.

3.3 Electron Beam Measurements

EBS device linearity is largely dependent upon the profile of the current density of the sheet electron beam. An accurate means is required to measure this profile. A special diode target called a "slit beam analyzer" shown schematically in Figure 3-5, was prepared for this purpose. The target contains 10 diodes, each having a metallized top surface with a narrow slit etched through the metallization to the active diode layer. If an electron beam is swept across this array as illustrated, each diode will respond only to the portion of the beam striking the narrow slit area. The current from each of the diodes in the array can be monitored and a profile of the beam density can be thus obtained.

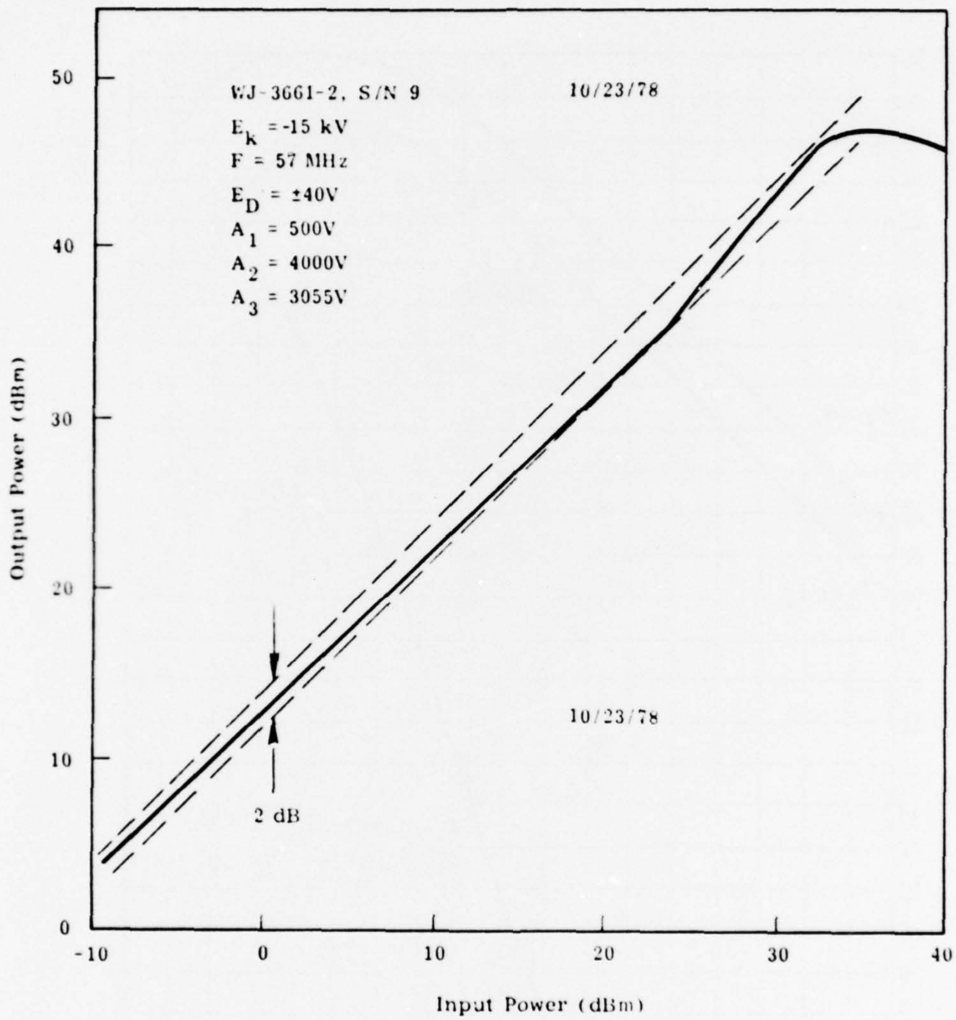

Figure 3-1. Linearity Measurement

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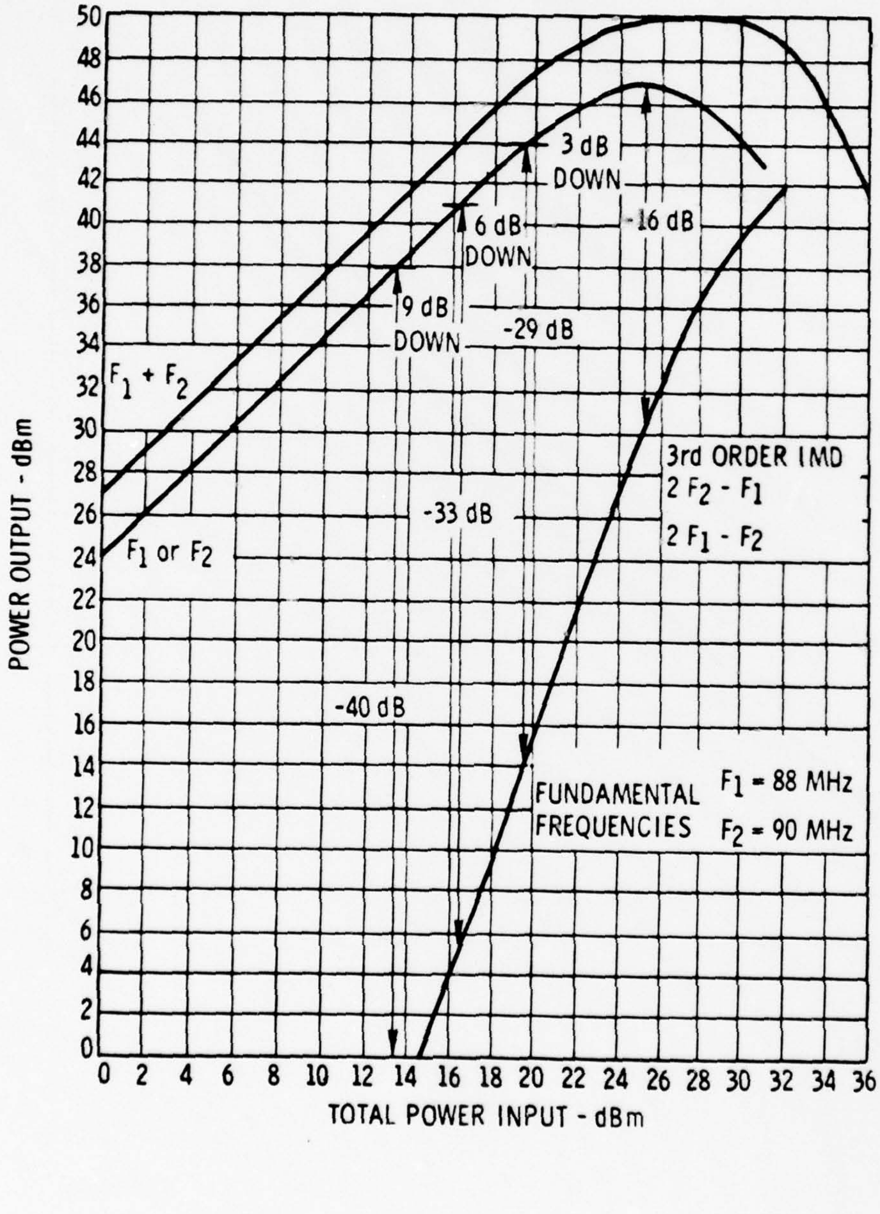

Figure 3-2. Third Order Intermodulation Products

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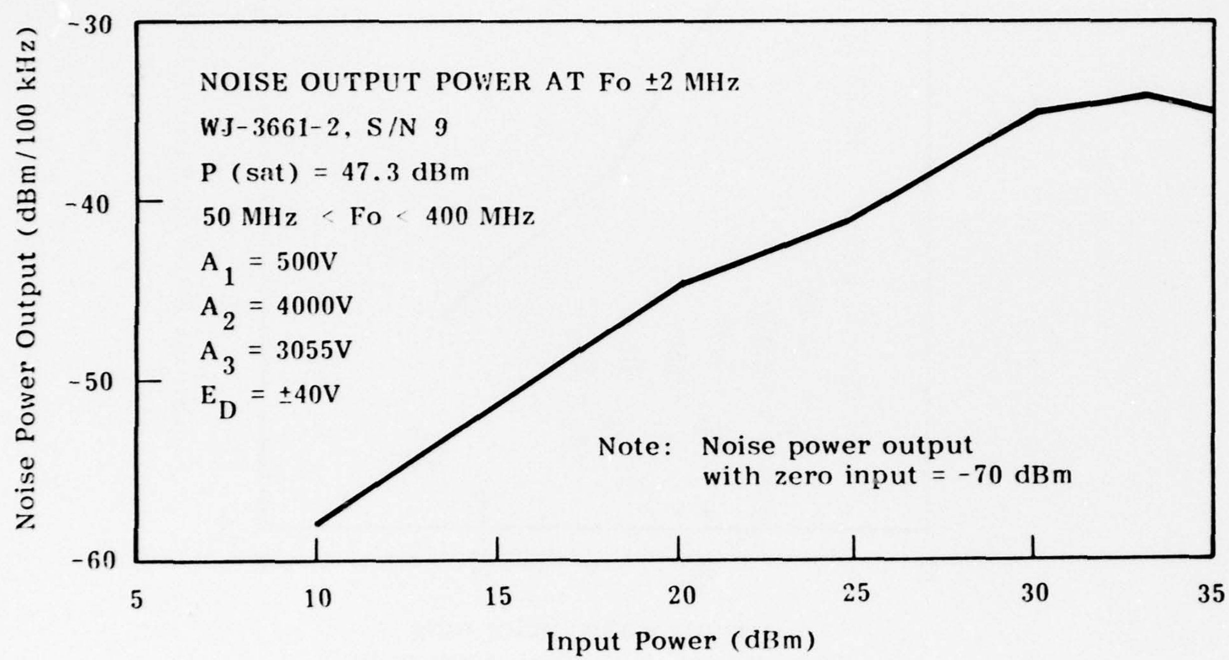

Figure 3-3. Noise Power Output

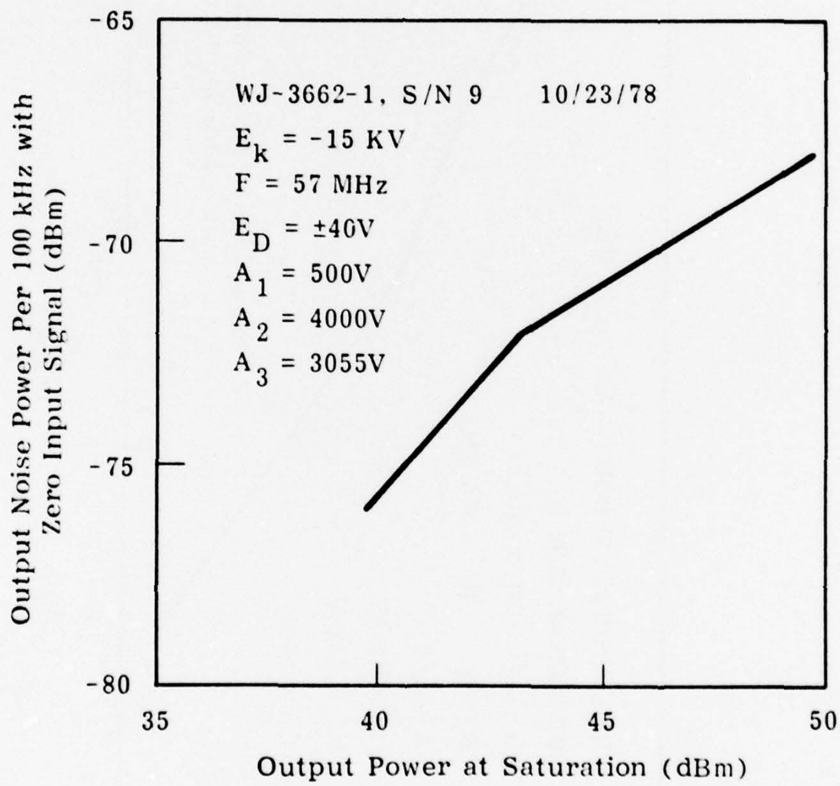

Figure 3-4. Noise Power with No Input Signal

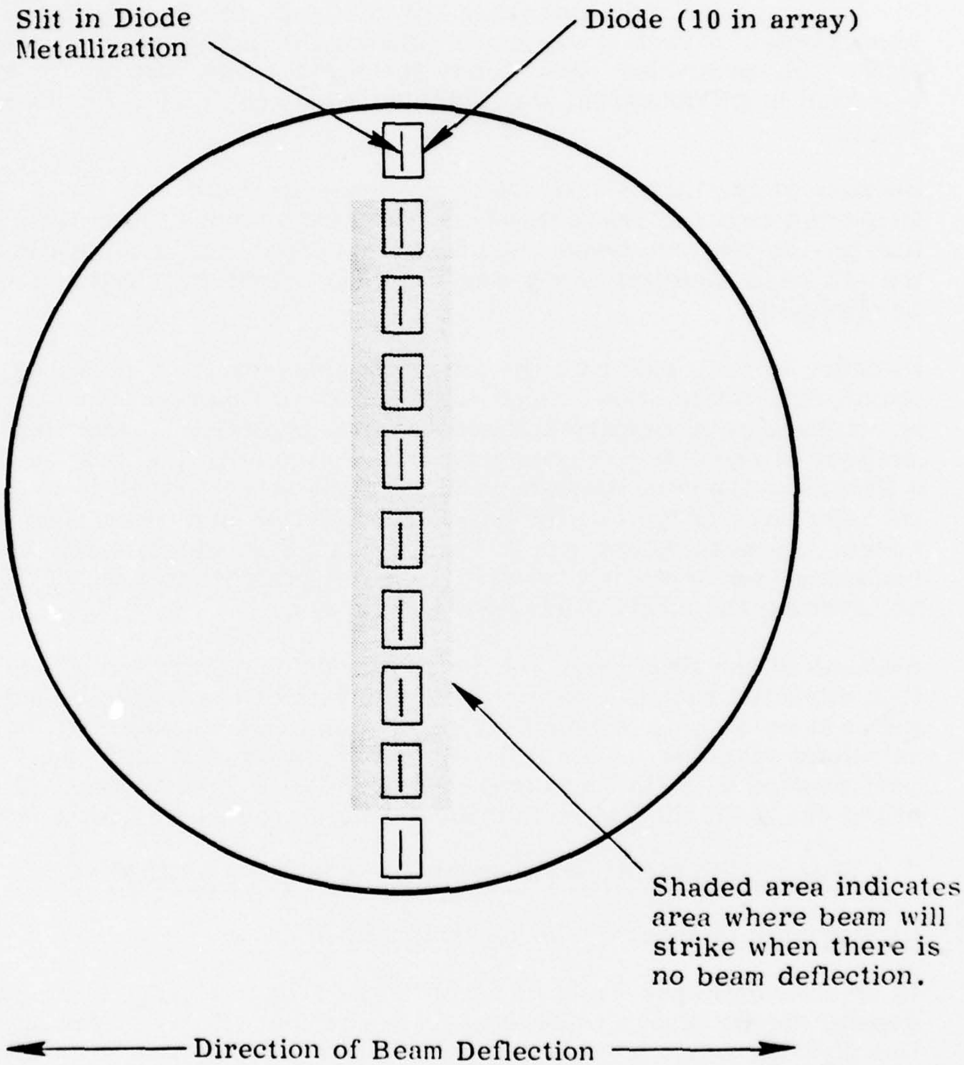

Figure 3-5. Slit Beam Analyzer Array

A slit beam analyzer target was assembled to an electron gun having the latest configuration as used for the 60 to 500 MHz high power EBS amplifiers.

The initial tests indicate that the beam exhibits moderate to severe distortion over approximately half the length of the target area. As the focusing electrode potentials are changed, the nature of the distortion changes in such a way as to indicate the likelihood of misalignment of the gun electrodes, specifically the third anode. However, a large variation in photocurrent was obtained from each of the diodes in the array.

Because of the inconsistencies of response from diode to diode, it was suspected that the array itself was not responding uniformly to excitation by the electron beam. It became apparent that a calibration of the slit beam analyzer array was required before meaningful data could be obtained.

In order to fully calibrate the slit beam analyzer, it is necessary to obtain data which shows diode response as a function of beam position at constant beam density and accelerating potential. Accordingly, two methods of obtaining this data were investigated. The best is the use of a Scanning Electron Microscope (SEM); the other method is to use a pencil beam electron gun of the same type used on high resolution cathode ray tubes. Because of the size of the EBS target mount into which the slit beam analyzer array is brazed, it was not possible to find an SEM capable of covering the entire surface of the array.

Because of the time which will be required for calibration of the array, it is expected that the beam profile analysis of the present electron gun will be slipped in time from November to March as shown on the milestone schedule. This will affect correlation of measured RF performance with the measured beam profile and therefore, will also affect the evaluation of the various effects of electron gun modifications.

4.0 MATHEMATICAL BASIS FOR DESIGN IMPROVEMENTS

4.1 Relationship of Beam Shape to Performance

In an EBS deflected beam RF amplifier, RF device efficiency and linearity depend on the design of several different components of the amplifier. Usually, the diode and matching circuits are treated as the crucial elements controlling EBS performance. The designs of the diode and matching circuits are carried through assuming that some means is available to perfectly modulate the beam current. Nonlinearities and RF efficiency reductions are then treated as arising only from the diode and circuit design.

A more thorough means of analyzing the linearity and efficiency of deflected beam amplifiers entails a careful analysis of the following beam parameters, as well as the usual target considerations:

1. The deflection sensitivity of the meander line versus frequency (and possibly amplitude),

2. The two dimensional beam density characteristic at the plane of the target under DC conditions, and

3. A consideration for any possible muddling effects at the target due to velocity differentials in the beam.

Item (3) has been investigated for the L band space amplifiers, and is apparently of little significance in the UHF band. The item of most importance, and the one which will be treated here, is (2).

The physical configuration of a deflected beam amplifier is shown in Figure 1-1. Figure 4-1 shows a close-up view of the EBS target with the dimensions to be used in the following analysis. The ideal beam density characteristic, shown in Figure 4-2, is a two dimensional step function, described by

$$J_o(x,y) = \frac{I_k}{d \cdot w} [u(x + d/2) - u(x - d/2)]\ [u(y + w/2) - u(y - w/2)] \qquad (1)$$

This analysis will consider deviations from the idealized expression (1) in the x direction, the direction of RF modulation.

Referring to **Figure 4-1**, if the center of the electron beam is deflected some distance x_o, the amount intercepted by the illuminated diode is

$$I(x_o) = w \cdot \int_{d/2 - x_o}^{3d/2 - x_o} J(x, 0)\, dx \qquad (2)$$

An equivalent form of (2) is

$$I(x) = I_k \cdot \int_{-\infty}^{\infty} f(\lambda - x)\ g(\lambda)\, d\lambda = f * g \qquad (3)$$

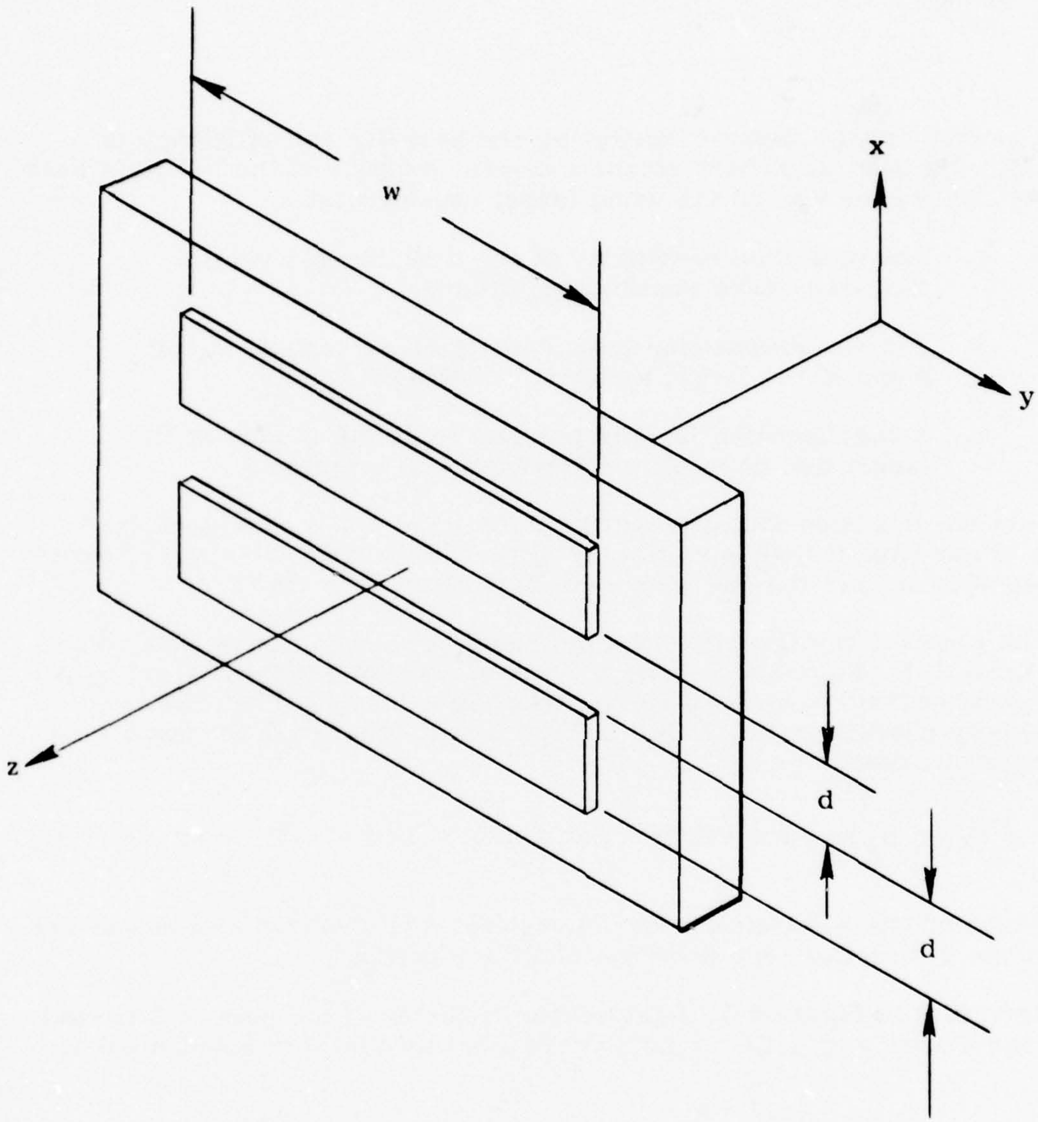

Figure 4-1. EBS Target Dimensions and x-y Coordinate Orientation

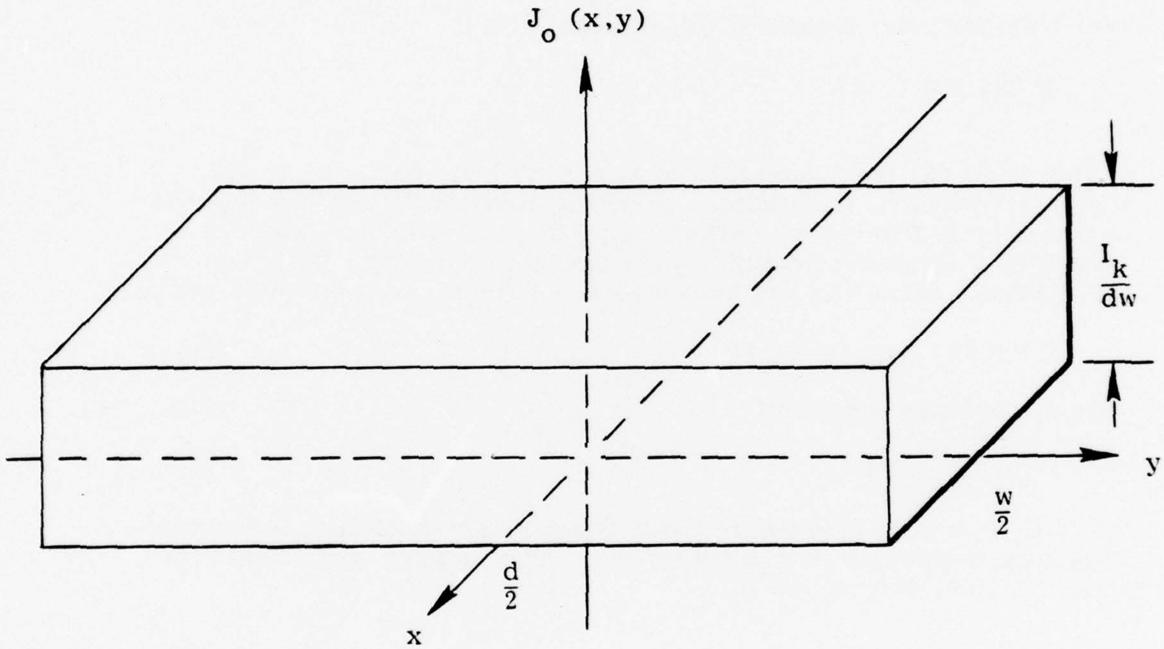

Figure 4-2. Ideal Beam Density Characteristic

where

$$f(x) = \frac{1}{d}[\ u(x - d/2) - u\ (x - 3d/2)\ ] \quad (4a)$$

$$g(x) = J(x,\ 0) \cdot w/I_k \quad (4b)$$

For this analysis, assume g (x) is even, i.e.,

$$g\ (x) = g\ (-x) \quad .$$

Expression (3) is in such a form as can be handled by 2-sided Laplace transform techniques, assuming that the function g (x) has a manageable transform. Alternately, if g (x) is in tabular form (such as a Gaussian profile), numerical convolution techniques are applicable. Once I (x) is known, one can then use the transformation

$$x = x\ (t) = d \sin\ (\omega_o t) \quad (5)$$

and a symmetry condition

$$I\ (-x) = I\ (x) \quad (6)$$

to find I(t). (This assumes the driving source deflects the beam a maximum distance d in one direction.) The Fourier coefficients for I(t) are then determined by

$$I(t) = I_o + \sum_{n=1}^{\infty} I_n \sin\ (n\ \omega_o t) \quad (7)$$

$$I_o = \frac{\omega_o}{2\pi} \int_o^{\omega_o/2\pi} I(t)\ dt \quad (7a)$$

$$I_n = \frac{\omega o}{\pi} \int_o^{\omega_o/2\pi} I(t) \sin\ (n\ \omega_o t)\ dt \quad (7b)$$

The power in each harmonic component is proportional to $|I_n|^2 R_n$, where R_n is the real part of the impedance presented to the nth harmonic by the matching circuit. Assume for simplicity that all of the R_n's are equal; then the beam efficiency may be defined as the ratio of power in the first harmonic to the total power:

$$\eta_b = \frac{|I_1|^2}{\sum_{n=o}^{\infty} |I_n|^2} \tag{8}$$

Note that the component I_o is not the same as the DC bias current calculated for target analysis. Under ideal conditions of beam uniformity for Class B operation,

$$I_o = 0$$

$$I_{dc} = \frac{1}{\pi} I_1 .$$

A way to visualize the quantity I_o is to think of it in terms of a D.C. spillover current under conditions of no RF drive and with the beam centered ($x = 0$). There is no similar quiescent analogue for the 2nd and higher harmonics, as these depend on the nature of beam nonuniformity.

4.2 Computer Aided Analysis

In order to perform rapid evaluation of design modifications, a computer program is required. Existing computer programs for prediction of beam profiles of circular beam guns, such as used in TWT's, were not readily usable in the case of the EBS due to the fact that they were intended to be used with electrode configurations for which the beam occupied a significant fraction of the enclosed volume. Our guns do not have this characteristic. Accordingly, a new program was initiated which will analyze the beam profile assuming a two dimensional gun geometry which is symmetrical about a plane lying on the axis of the gun and parallel to the long edge of the cathode face.

5.0 ELECTRON GUN MODIFICATIONS

In order to provide an electron gun having greater mechanical and electrical stability, the supporting structure and vacuum envelope of the present gun was re-designed. The new design uses metal-ceramic construction and entirely eliminates the use of glass. The electrode geometry remains the same for the first prototype metal-ceramic gun, but can be easily modified as the program proceeds.

All parts for the new gun have been designed and placed on order.

6.0 PROGRAM FOR THE NEXT REPORTING PERIOD

6.1 Performance Data of Existing EBS Amplifiers

Additional data must be taken on the existing EBS amplifiers. In the area of noise measurements, the data must be repeated because the signal source did not have sufficient spectral purity to prevent the measurements from being influenced by noise from the source itself.

The intermodulation data is not yet complete because it does not compare efficiency with the level of intermodulation products. The deflected beam amplifier runs in a Class AB mode when adjusted for optimum linearity and efficiency. The width of the beam with respect to the spacing between the halves of the diode array determines the operating point, and the optimum beam width for efficiency is not the same as that for best linearity. Therefore, it is valuable for comparison purposes to obtain data of intermodulation products versus efficiency. The gun design can then be modified to bring the optimum linearity and efficiency operating points closer together. Also, this data must be taken on a device having the longer cathode and larger diode area of the most recent device configuration.

6.2 Electron Beam Analysis

Characterization of the slit analyzer array must be accomplished so that meaningful measurements of electron beam profile can be obtained. For this purpose, a pencil beam electron gun having high resolution will be purchased from the Stewart Division of the Watkins-Johnson Company. The gun will be mounted to the slit analyzer array and the beam will be swept over the diode array by means of a deflection coil. The current output by each diode will be recorded and a mapping of the diode sensitivity versus beam position can be made.

The slit analyzer will then be used to measure the beam profile of the standard EBS electron gun used on the same device on which linearity data was measured. A correlation between beam shape and linearity can then be made.

6.3 Computer Programs

During the next reporting period the computer program for analysis of beam profile from a given electrode geometry will be completed. A computer analysis will then be made of the present gun and the resulting calculated beam profile will be compared with beam profile measurements of the same gun.

A second computer program exists which gives the value of IM products and harmonic distortion for a given beam profile. This program will be checked for accuracy and then used to correlate the measured IM and harmonic data with the measured electron beam profile of the present gun.

6.4 Electron Gun Modifications

Using the correlation between measured beam profiles of the present gun and the beam profiles predicted by the gun analysis program, proposed modifications to the electrode geometry will be evaluated for their effect on beam profile. This will form a basis for actual modifications to the electron gun to obtain a more ideal beam profile.

KEY PERSONNEL

DR. DEAN A. WATKINS, Chairman of the Board and Chief Executive Officer. Born October 23, 1922, Omaha, Nebraska. Thirty-four years experience. B.S., Iowa State College, 1944; M.S., California Institute of Technology, 1947; Ph.D., Stanford University, 1951.

Dr. Watkins was a co-founder of Watkins-Johnson Company in 1957. His faculty association with Stanford University began in the spring of 1953, when he was appointed Associate Professor of Electrical Engineering. He was advanced to full professorship in June of 1956 in which he continued until December of 1963.

Previously, (1951-1953) he was with the Research Laboratories of the Hughes Aircraft Company, Culver City, California, where he designed and tested the first helix backward-wave oscillator. He later became Head of the Microwave Tube Department. Early in his career he was a design engineer for Collins Radio Company, Cedar Rapids, Iowa. He spent a year during 1948-1949 on the staff of Los Alamos Scientific Laboratory.

At the 1957 Western Electronic Show and Convention in San Francisco (for which he was chairman of the Technical Program Committee), Dr. Watkins was named recipient of the annual Electronic Achievement Award of the Seventh Region of the Institute of Radio Engineers. This honor is given each year for outstanding contributions to electronic activities in the nine Western states embraced by the Seventh Region. In 1958, he was named a Fellow of the IRE, now the IEEE. He was a director and chairman of the San Francisco Council of the Western Electronic Manufacturers Association, now American Electronics Association (AEA). He was a consultant of electron devices to the Director of Defense Research and Engineering from 1956 to 1966. He was elected to the National Academy of Engineering in 1968. He became a member of the Defense Orientation Conference Association in 1973. He served as Trustee, Stanford University from 1967 to 1969; and as a Member, Advisory Council of the School of Engineering at Stanford from 1970 to present. He was appointed a Member of the Board of Regents of the University of California in 1969, and served as Chairman of that board from 1972 to 1974. He has served as a Member of the Board of Overseers of Hoover Institution on War, Revolution and Peace from 1969 to present; as a Member, National Security Industrial Association Board of Trustees, 1975 to the present; as Director, California Chamber of Commerce, 1975 to the present, and Treasurer 1978; as a Member, Santa Clara County Jr. Achievement Advisory Policy Committee, 1975 to the present; and as a Member, Board of Trustees of the U.S. Council of the International Chamber of Commerce, 1978.

Dr. Dean A. Watkins (Continued)

He is listed in "Who's Who in America", Who's Who in Finance and Industry" and "American Men and Women of Science".

While a student at Stanford, Dr. Watkins was co-inventor of the low-noise traveling-wave tube, a development announced in 1952. He is author of numerous technical publications and a book, "Topics in Electromagnetic Theory".

PUBLICATIONS

Dr. Dean A. Watkins,

"The ten-channel electro-static pulse analyzer, "Rev. of Sci. Inst., vol. 20, No. 7; July, 1949.

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"Effect of velocity distribution on traveling-wave tube gain," with N. Rynn, Jour. Appl. Phys., vol. 25, No. 11: November, 1954.

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Publications - Dr. Dean A. Watkins, (Continued)

"Helix millimeter-wave tube," with W. V. Christensen, Proc. IRE, vol. 43, No. 1; January, 1955.

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Dr. Dean A. Watkins	Date	Patent Number
Patents Issued		
Low-noise Traveling-wave Tubes with L. M. Field	23 July 1957	2,800,602
Traveling-wave Tube (Helix having a stop-band) with H. R. Johnson	8 October 1957	2,809,321
Traveling-wave Tube Automatic Gain Control	26 June 1956	2,752,430
Helitron Oscillator	18 August 1959	2,900,558
Microwave Tube	4 November 1958	2,859,374
Bar-strapped multifilar Helix for Traveling-wave Tube	22 August 1961	2,997,618
Reflex Space-harmonic Oscillator	13 January 1959	2,896,019
Patents Applied For	**Date Filed**	**Serial Number**
Plasma-wave Amplifier with C. K. Birdsall	18 December 1952	326,632

DR. H. RICHARD JOHNSON, President. Born April 26, 1926, Jersey City, New Jersey. Thirty-two years experience. B. S. E. E. with Distinction, Cornell University, 1946; Ph. D., Physics, Massachusetts Institute of Technology, 1952.

Dr. Johnson participated in the founding of Watkins-Johnson Company in 1957. He has served on panels of the Scientific Advisory Board of the Director of the National Security Agency. He has been a Lecturer in Electrical Engineering at Stanford University and at the University of California in Los Angeles.

From 1952 to 1957, he was employed by the Hughes Aircraft Company, Culver City, California, where he performed research and development work in the fields of traveling-wave and backward-wave oscillator tubes.

From 1946 to 1951 Dr. Johnson attended M. I. T. under a Research Laboratory of Electronics Fellowship, His thesis involved microwave spectroscopy.

Dr. Johnson is the author or co-author of twenty-one publications and eight patents. He is listed in "Who's Who in America", and "American Men of Science", and has received honorable mention in Eta Kappa Nu's "Outstanding Young Electrical Engineer" awards for 1956. He is a Fellow of the Institute of Electrical and Electronics Engineers and a member of the National Academy of Engineering, the American Physical Society and the Association of Old Crows. He is past chairman of the Los Angeles Professional Group on Electron Devices, the Wescon technical program committee and the local United Fund Campaign. He is past President and Board member of the Stanford Area Council of the Boy Scouts of America and recipient of the Silver Beaver Award. He was a director of WEMA and of Volunteers in Technical Assistance.

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PATENTS

Dr. H. Richard Johnson

Patents Issued	Date	Patent Number
Transition from Bifilar Helix to Waveguide for Backward-wave Oscillator	17 September 1957	2,806,975
Traveling-wave Tube with D. A. Watkins	8 October 1957	2,809,321
Traveling-wave Mixer Tube (Means for obtaining large phase shift per modulating volt)	11 August 1959	2,899,596
Backward-wave Oscillator (Separating beam and circuit for minimum frequency pulling)	11 August 1959	2,899,594
Frequency-sweep Circuit for Backward-wave Oscillators (To generate linear frequency vs. time characteristics)	21 January 1958	2,820,901
Traveling-wave Tube (Means for focusing hollow beams) with G. R. Brewer and C. K. Birdsall	29 October 1957	2,811,663
Traveling-wave Tube (Elimination of spurious backward-wave oscillations through velocity spread in beam)	14 June 1960	2,941,113
Periodically Focused Traveling-wave Tube with D. J. Bates and O. T. Purl	23 May 1961	2,985,792

DOUGLAS B. CLARK, Member of the Technical Staff, Tube Division, Devices Group. Born December 31, 1946, Oakland, California. Nine years experience. B.S., Electrical Engineering, University of California at Berkeley, 1969. Graduate studies in Electrical Engineering at Loyola University of Los Angeles.

Mr. Clark is currently a Project Engineer with the Electron Bombarded Semiconductors Group. He is responsible for design and development of state-of-the-art EBS devices.

From February 1974 to May 1977, Mr. Clark was with the Solid State West Division of Varian Associates in Palo Alto, California. He was Project Engineer on a variety of development and production projects involving Gun diode amplifiers, YIG-tuned Gunn Oscillators, and bipolar transistor amplifiers.

From June 1969 to February 1974, Mr. Clark was with the Hughes Aircraft Company, Electron Dynamics Division, where he was a Member of the Technical Staff. His responsibilities included that of Project Engineer on state-of-the-art, dual mode, multi-octave traveling-wave tubes. He also was responsible for production of high pulse power space tubes.

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Mr. Rettig is presently working on the development of an EBS space amplifier for NASA Goddard Research Center that must meet stringent linearity and efficiency specifications.

Formerly he was a research assistant at Purdue University, engaged in High Gradient Magnetic Separation studies. This involved experimental quantization of 3-dimensional buildups of small paramagnetic particles on saturated ferromagnetic wires.

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SALVATORE SPINELLA, Head, EBS Engineering Section, Tube Division, Devices Group. Born May 19, 1943, Panama City, Panama. Eleven years experience. B.S.E.E., University of California at Berkeley, 1965; M.S.E.E., San Jose University, 1971.

Mr. Spinella is currently Head, EBS Engineering Section and is responsible for the direction of research and development on a variety of Electron Bombarded Semiconductors including high power RF amplifiers, video amplifiers, and signal processing components.

From October 1974 until June 1978, Mr. Spinella was a Member of the Technical Staff in the EBS Engineering Section with overall responsibility for setting-up, maintaining, and sustaining the in-house diode facility. He was engaged in the design, development, and fabrication of EBS diodes for the generation of high voltage and high current fast rise-time pulses. Mr. Spinella was responsible for the development of diode processing that results in breakdown voltages approaching theoretical values as well as in high yields.

From December 1973 to September 1974, he was Fabrication Manager at Advanced Micro Devices in charge of manufacturing state-of-the-art bipolar and MOS integrated circuits.

From March 1973 to December 1973, he was MOS Operations Manager at Antex in charge of manufacturing electronic watches and calculators.

From March 1970 to March 1973, he was Fabrication Manager at Advanced Micro Devices in charge of manufacturing state-of-the-art linear and digital integrated circuits.

From August 1965 to March 1970, he was at Signetics Corporation where he held various positions ranging from Processing Engineer to Section Head of the Engineering Pilot Line, to Section Head of Sustaining Engineering.

Mr. Spinella is a member of ETA Kappa Nu, and of The Electrochemical Society.

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"Electron-Bombarded Semiconductor Devices," Advances in Electronics and Electron Physics, Vol. 44, 1977, pp 221-281, Academic Press, with D. J. Bates, R. I. Knight and A. Silzars.

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